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ASSESSMENT OF POST-EARTHQUAKE AVAILABILITY OF HOSPITAL SYSTEM AND UPGRADING STRATEGIES

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SUMMARY

A model for the regional hospitals system behaviour in case of a seismic event is developed. The aim is the evaluation of the vulnerability of the system as well as the selection of the best intervention strategy for the retrofitting of the hospitals so as to minimize the cost benefit ratio and to evaluate the effect of different post-earthquake emergency measures like the use of camp hospitals. The efficiency of the system is measured in terms of the mean distance to be cured for persons injured by the earthquake and by damages to the system. Some simplifying assumptions are used and discussed; these can be easily removed if necessary. Results allow to clearly indicate the most convenient interventions. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: seismic reliability; fragility; lifelines; hospitals; random variables; structural reliability

INTRODUCTION

Hospitals are central in minimizing inconveniences to population, in case of seismic events; nonetheless their seismic safety is generally low. Hospitals are, in fact, complex systems, containing a large quantity of seismically fragile machinery, often more fragile than the structures containing them.

The retrofitting of existing hospitals is a crucial problem. Structural types are extremely varied in many countries (e.g. Europe), comprising masonry and r.c. buildings, designed according to the norms of the construction period; these, as the present ones also, with the possible exception of the recent Californian code for new hospitals, are inadequate for these type of structures.

At a regional level, one can observe that the lack of functioning of a single hospital influences the services demanded to the remaining ones, because of transportation to the nearby hospitals. The analysis of the problems relating to existing hospitals considered as a regional system, can usefully complement information concerning the retrofitting of existing ones.

One can employ various indexes to measure the regional system response. Namely, one can look both at direct damages on hospitals and at the worsening of the service quality offered by the system. In this work, attention is focused on both aspects. As for the system behaviour, the index distance covered by each casualty seems an informative parameter. The distance per casualty is computed, given a seismic event, by evaluating each hospital in terms of number of available beds and the number of casualties in each municipality. Casualties are sent from each municipality to the nearest hospital up to its actual capacity; the average distance covered by each casualty is then evaluated.

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The procedure determines the most critical hospitals, i.e. those ones whose functioning has the largest influence on the system behaviour. The effectiveness of the various levels and strategies of intervention is hence evaluated and it is possible to identify the most convenient one.

Some of the assumptions which will be made in this work, such as the unique fragility for all hospitals and the correlation law between earthquake intensity and casualties, can be refined; however, the presented procedure is general and can account for more detailed models of the single aspects.

This work is part of a more general research involving existing hospitals in seismic areas; research developments have concerned detailed vulnerability analyses of single hospitals[1–3], where the single hospital is analysed as a system composed of series or parallel subsystems and the limiting factor is the functioning of the operating theaters; scenario studies of damages in past earthquakes;[4,5] finally studies concerning the behaviour of regional hospital systems.

PERFORMANCE INDEXES FOR THE REGIONAL HOSPITALS SYSTEM

The mortality rate of casualties, in case of seismic event, is substantially reduced if they receive care in a short time. Time depends both on the distance to reach hospitals and on the average transportation speed. Unfortunately, after a strong earthquake both these quantities tend towards undesired values, the former increasing and the latter decreasing, because of:

- damage and/or congestion of hospitals,
- damage and/or congestion of the transportation network.

The former causes a strong increase in the distance to cover because casualties exceeding the hospitals' capacity have to be moved to non full ones. The latter causes a decrease in the transportation speed and an increase in the distance to cover to reach hospitals, e.g. because of interrupted transportation links.

In the present work only damage to the hospitals is modelled, though the importance of damage to the transportation network is acknowledged. This will be considered in a successive development stage of the present model.

Attention has been focused on finding a parameter which could synthetically define the global performance of the network and was sufficiently descriptive; the *distance*, as the crow flies, *covered by each casualty*, to be defined in a probabilistic sense, seemed apt to fulfil the scopes. This parameter, in fact, under the assumption of uniform distribution of the transportation links, acceptable in a developed region at a large scale, is proportional to the time elapsed before a casualty is cured. Its reduction lowers the mortality rate. In normal conditions, the CDF of distances between an Abruzzo inhabitant and the nearest hospital has been computed with the statistical data of the Italian State Agency;[6–7] the curve is shown in Figure 1.

It shows that about 45% of the inhabitants of Abruzzo live in municipalities which contain hospitals (distance equal to zero km) and 96% of the population finds a hospital at less than 15 km. CDFs and average values are compared with those computed in case of a seismic event, and with various retrofitting schemes. A comparison evaluates the loss of efficiency due to earthquakes and the comparative testing of the different retrofitting schemes.

A key issue is how to instruct sanitary managers about managing casualties exceeding hospitals' capacity. In order to save vital time, it would be desirable to instruct them about their destination without having to wait for exchange of information among hospitals. To this end, it was decided to also compute the statistics of a second parameter, the *coefficient of occupation* of hospitals, i.e. the ratio of patients to the nominal number of beds. In Italy, this value is normally worth about 70%; 100% indicates that all beds are taken.

A third important parameter is the damage to each hospital, in terms of *number of bed–losses*. This is assumed proportional to the direct costs of earthquake damage. It must be stressed that it is independent on the hospitals system, like behaviour, since there is no interaction between direct damages at different hospitals.

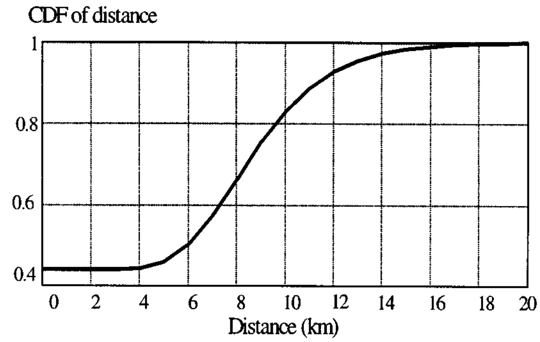

Figure 1. CDF of distances to reach hospitals in Abruzzo

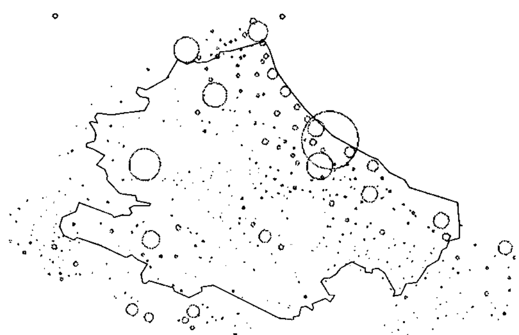

Figure 2. Distribution of the population in Abruzzo

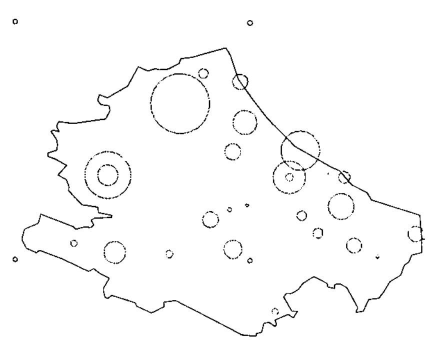

Figure 3. Distribution of hospitals in Abruzzo

MODEL OF THE HOSPITAL SYSTEM UNDER SEISMIC EVENT

The regional system: population and hospitals' distribution on the territory

Abruzzo has a population of about 1 300 000 with low density; the major centres, L'Aquila and Pescara, have about 100 000 inhabitants and the remaining population is rather uniformly distributed on the territory (see Figure 2; circumference radios are proportional to inhabitants of each municipality and the largest circumference represents 120 000 inhabitants).

The hospital location follows population distribution rather closely (see Figure 3, the largest circumference representing 1369 beds available). 25 hospitals of the region and their capacities are listed in Table I.

Table I: Hospitals in Abruzzo

Number	Capacity (n. beds)	Municipality name	Hospital name
1	552	Atri	S.Liberatore
2	501	Avezzano	Ss Filippo
3	165	Pescina	Rinaldi
4	150	Tagliacozzo	Umberto I
5	150	Castel Di Sangro	Civile
6	750	Chieti	Ss Annunziata
7	178	Chieti (Chieti scalo)	San Camillo De' L.
8	220	Guardiagrele	Maria Ss Immacolata
9	350	Giulianova	Maria Ss.Ma D.S.
10	1073	L'Aquila	San Salvatore
11	470	L'Aquila	S. Maria C.
12	597	Lanciano	Lanciano
13	345	Atessa	Atessa
14	224	Casoli	Casoli
15	221	Sant'omero	Val Vibrata
16	262	Ortona	Berna
17	370	Penne	S.Massimo
18	901	Pescara	Civile Dello Spirito
19	365	Popoli	Ss.Trinita'
20	95	Tocco Da Casauria	Domenico Filomusi
21	64	San Valentino I	Presidio
22	420	Sulmona	Dell'Annunziata
23	1369	Teramo	Riuniti
24	347	Vasto	Presidio
25	72	Gissi	Presidio

Casualties, fragility of buildings and hospitals

The relationship between earthquake intensity and mean number of casualties as a percentage of the population, $\bar{C}(I)$, can be derived on the basis of the data on building types and quantity. Buildings' fragility and their coefficient of occupation are strictly related to the casualties after the earthquake. For a discussion one can make reference to Coburn and Spence;[8] data on buildings and their occupation coefficient are drawn from Colozza *et al.*,[6] data on population are taken from the census.[7] The following relationship (1), plotted as a solid line in figure 4, has been employed:

$$\bar{C}(I) = (I - I_{\min})^4 \, 0{\cdot}00048 \tag{1}$$

where $I_{\min} = 7$ MM.

In order to ascertain the influence of the assumed (and questionable) intensity—casualties law on the results, a preliminary sensitivity analysis has been performed with relationship (1) increased/decreased by 33% (dotted lines in Figure 4). A change in the numerical values of the results has been lower than about 5%, which is the reason why equation (1) has been retained in all the subsequent analyses.

Building types and years of construction for hospitals are variable; nonetheless, since most of them are post World War II r.c. constructions, a single fragility function,[3] has been considered a reasonable approximation to the real fragility functions and has been retained in this work. The implemented procedure allows, without any change, to account for different fragility functions for different hospitals.

The probability of failure of the single hospital modelled as a system[3] is shown in Figure 5; the curved arrows indicate retrofitting from the current fragility level, $A - C$, to non structural bracing, $C' - D$, to infill wall retrofitting, minor structural retrofitting and some relocations, $D'' - E$. The limit state considered was

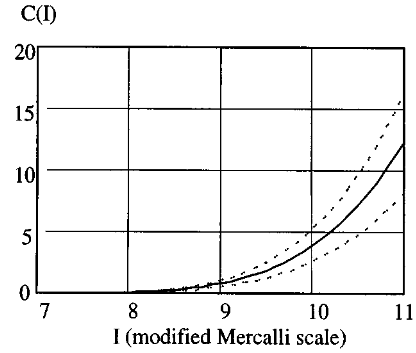

Figure 4. Casualties as a percentage of population

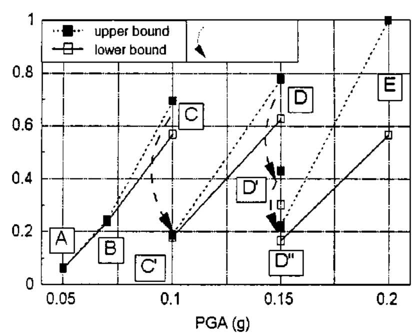

Figure 5. Probability of failure of a hospital[3]

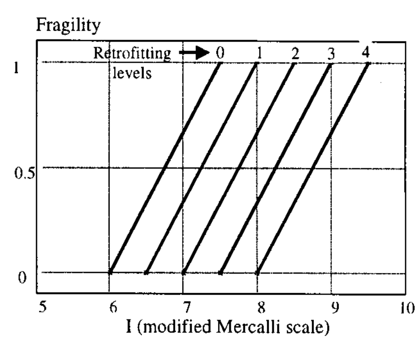

Figure 6. Assumed damage curves

the loss of functioning of the operating theaters. In the present study, the mean value of the hospitals' fragility is represented via a damage indicator which may vary between 0 (no damage) and 1 (total collapse); this expresses the ratio between the number of available beds before and after the earthquake; thus the number of unavailable beds in each hospital, given the seismic intensity, is computed by multiplying the damage times the initial number of beds. A total of five damage curves have been considered, which are levels 0 to 4 in Figure 6, each one corresponding to a different upgrading level. The first three levels have been derived from

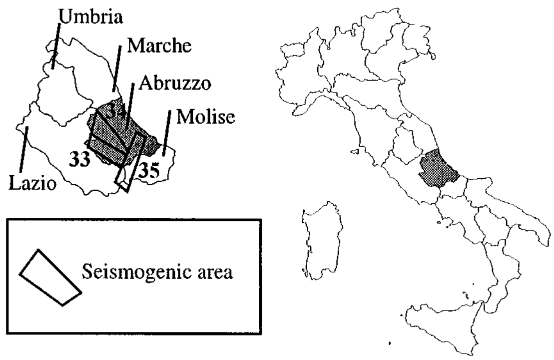

Figure 7. Seismogenic areas

Table II. Parameters of the seismogenic areas

Region	$i_{\min}$	$i_{\max}$	λ	β
33	6·0	11	0·464	0·373
34	6·0	10	0·337	0·701
35	6·0	10	0·122	1·527

Figure 5 ($A - C$, $C' - D$, $D'' - E$), under the assumptions of no damage (damage indicator equal 0) for $P_f < 0{\cdot}2$ and of complete collapse for $P_f > 0{\cdot}6$. The curves of levels 3 and 4 are further shown, obtained from the previous levels with half an MM degree translation and corresponding to assumed higher retrofitting levels.

In the analyses, damage to hospitals and ratio of casualties to the population are modelled as lognormal r.v., with mean values functions of the earthquakes intensities as discussed previously and c.o.v. equal to 15%.

Earthquake model

The classical Cornell model, with diffused seismicity, has been assumed for earthquake generation. After a preliminary check aimed at identifying the seismogenic areas influencing the hospital system in Abruzzo, the three seismogenic areas shown in Figure 7 have been selected. In each seismogenic area, the coordinates of the epicentre are independent random variables with a constant distribution between the minimum and maximum values of the coordinates of the points of the area.

The Poisson model for the time succession of earthquakes is retained and the intensity distribution given an event which is modelled via the doubly truncated Gutenberg–Richter law

$$\lambda(i) = \lambda(i_{\mathrm{MIN}}) \cdot [1 - F_{\mathrm{I}}(i)]; F_{\mathrm{I}}(i) = 1 - \frac{\exp(-\beta \cdot i) - \exp(-\beta \cdot i_{\mathrm{MAX}})}{\exp(-\beta \cdot i_{\mathrm{MIN}}) - \exp(-\beta \cdot i_{\mathrm{MAX}})} \tag{2}$$

β = severity parameter; $i_{\mathrm{MIN}}[i_{\mathrm{MAX}}]$ = lower [upper] bound for the earthquake's intensity

The parameters of the Gutenberg–Richter law are evaluated on the basis of the historical seismicity[9] and are shown in Table II (intensity is in modified Mercalli scale).

The minimum assumed intensity $i_{\min} = 6$ MM is the minimum value for an earthquake to cause damage to hospitals and buildings.

A circular attenuation law:[9]

$$\Delta I_s(R) = a + b \cdot (R + R_0) + c \cdot \log(R + R_0) + \varepsilon \quad (3)$$

fitted with a maximum-likelihood method has been adopted. Its parameters

$$R_0 = 3 \text{ Km}; \quad a = -0{\cdot}5; b = 4{\cdot}43; \qquad c = 0{\cdot}056, \varepsilon = N(0; \sigma_\varepsilon = 1{\cdot}037).$$

have been calibrated using registration of events in central Italy.

Simulation procedure

The statistical properties of the performance indexes: distance per casualty, coefficient of occupation and number of bed losses have been computed with a numerical simulation procedure (Monte-carlo scheme) based on the following steps:

1. at time $t = 0$, sample of the epicentral coordinates and intensity of the earthquake
2. attenuation of intensity at municipalities and hospitals sites,
3. at time $t = 0$, i.e. immediately after the earthquake has struck:
   3.1 sample of the casualties at municipalities and of damage at the hospitals
      3.1.1 at municipalities; sample of the number of casualties
      3.1.2 at hospitals; sample of the damage which results in bed losses. Check of whether the hospital capacity.
      (NLU beds) is sufficient for the patients already being treated (NFP).
      If NFP > NLU, hospitals become a departure point for casualties
   3.2 transportation of casualties from the municipalities and from the filled hospitals
      3.2.1 at municipalities: transportation of casualties to the nearest hospital, with no exchange of information
      3.2.2 at hospitals: transportation of casualties to the nearest and not full hospitals, with exchange of information
4. at time $t > 0$, at hospital h where casualties arrive, check of its capacity. If it cannot treat some patients, transportation of exceeding casualties to the nearest and not full hospitals, with exchange of information
5. repetition of the cycle until all casualties have been cared for in all the hospitals
6. repetition of the simulation until the c.o.v. of the performance index of the system is lower than an input prescribed value.

The simulation for Abruzzo has taken into account all of the hospitals within the region (25 hospitals, listed in Table I) and also the hospitals in the neighbourhood regions of Marche, Lazio and Molise: in fact, in case of strong seismic events, the hospitals in those regions are used.

Also, the municipalities outside Abruzzi and at a distance smaller than 20 km (corresponding to an attenuation of 2 Mercalli degrees according to the deterministic part of a equation (3) has been taken into account, for it has been checked that there is an important interaction.

An example of the steps followed, which can further clarify the procedure, is shown in Appendix 1.

Computational time for the implemented procedure has been reasonable since the choice of the c.o.v. of the estimators (indicated with the hat sign) of the mean value of performance indexes.

$$\hat{\delta}_m = \frac{1}{\sqrt{N}} \cdot \frac{\hat{\sigma}}{\hat{\mu}}; \hat{\mu} = m = \frac{\sum_{i=1}^{N} x_i}{N}; \hat{\sigma} = s = \sqrt{\frac{1}{N-1} \cdot \left(\sum_{i=1}^{N} x_i^2 - N \cdot m^2 \right)}$$

to be lower than 10% has required an average 1000 simulations for each seismogenic area, with a computation time of about 1 h, on a 586/130 MHz PC; the program has been written in Fortran and linked with Microsoft Power Station 4.0.

RESULTS

Introduction

The improvements in the structural seismic behaviour benefit the system in a twofold fashion: (1) better service for the hospitals' users and equation (2) lower repairing costs for the hospitals' owners.

The performance indexes chosen are the *distance covered per casualty* and the *coefficient of occupation*, to quantify equation (1), and the *number of bed losses*, to quantify equation (2), or some simple algebraic elaboration of them. It is worth noting that the distance per casualty is a more informative performance index as compared to bed losses; bed losses, in fact, do not account for the behaviour of the hospitals as a network system serving the population in the area but only quantifies the seismic risk at each hospital location. The bias for decision taking should hence be towards such performance indexes as distance per casualty or a weighted one including more criteria; the meaning and use of these indexes has been already briefly discussed in the second chapter.

Analyses (1) compare the effect of hospital upgrading versus the reduction of distance per casualty; this means substantially shorter time before a casualty is cured which in turn implies lower mortality rates. The input (structural upgrading) and the output (increase/decrease of distance per casualty) quantities have not been compared on a homogeneous (e.g. monetary) basis because the result would be, in the authors' opinion, highly questionable. It would be, in fact, necessary to use correlation laws firstly between the distance covered to reach hospitals and the time before a casualty is cured, and secondly between the time and monetary value of lower mortality rates. This is in principle computable via correlation analyses using reliable data, but a highly data dependent. Analyses (1) are conditioned to a seismic event in seismogenic areas and answer the following questions:

- which hospital, in a network, should be chosen to be first retrofitted,
- which retrofitting level is more convenient,
- what is the effect of some common emergency measures (installing camp hospitals, increasing the capacity of hospitals for emergency),
- which location should be chosen to build a new hospital,
- which hospitals are likely to be not full in case of a strong seismic event

and are especially suited to assess the relative effectiveness of intervention decisions.

Analyses (2) compare the numbers of upgraded beds to damaged (and hence unavailable) beds due to seismic action; since the input and output quantities are homogeneous, a cost-benefit analysis was performed. These are conditioned to a period of observation (1 yr) and answer the following questions:

- which is the gain, in terms of reduction in bed losses, of retrofitting interventions
- which is the pay-back period for a retrofitting intervention,

In the sequel the suffix b (e.g. 1.b) indicates results normalized to the input allocated resources (for the present case, number of beds in seismically retrofitted hospitals), whereas the suffix a stands for not normalized results.

In more details, analyses (1) consist of five investigations (1.a to 1.e):

(1.a) Identification of the retrofitted hospitals to which the maximum benefit is associated.

Analyses have been carried out considering the fragility of a single hospital at level 1 or 2, while maintaining the fragilities of the remaining hospitals at level 0 (see Figure 6).

Retrofitting of a single hospital, at levels 1 or 2, brings about some decrease in the value of the distance that each casualty has to cover; the maximum obtainable improvement is that associated with a hospital network in which hospitals are not fragile. It has been chosen to express improvements associated with retrofitting of a single hospital normalized to the maximum possible improvement, i.e.:

$$i1\mathrm{a}(H, F) = \frac{r(0) - r(H, F)}{r(0) - r(\infty)} \tag{4}$$

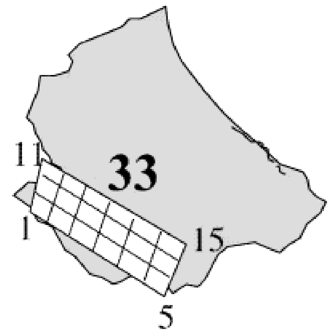

Figure 8. Subregions in seismogenic area 33

where $r(H, F)$ is the mean value of the distance per casualty after retrofitting of hospital H at levels F(1 or 2), $r(0)$ and $r(\infty)$ indicate the same quantity with the hospitals respectively in the current state and in the state such that they are not fragile, ∞ level.

Since results are computed via numerical simulation, it has also been possible to calculate the CDF of distance per casualty. This was done for levels 0 and ∞ and after retrofitting intervention on selected hospitals; curves have been compared with the CDF in normal conditions in Abruzzo.

(1.b) As (1.a), per unit retrofitting intervention.

Retrofitting of a hospital would normally be accomplished by intervening on all its facilities at the same time and hence analysis (1.a) is reasonable. However, results are biased towards larger improvements for larger hospitals, whereas it would also be interesting to compare improvements for unit retrofitting cost. Under the assumption that retrofitting cost is directly proportional to the number of beds in a hospital, improvement for unit retrofitting cost may be simply computed dividing the results achieved in (1.a) by the number of beds:

$$i1\mathrm{b}(H, F) = \frac{r(0) - r(H, F)}{r(0) - r(\infty)} \cdot \frac{1}{n\mathrm{b}(H)} \tag{5}$$

where nb(H) is the number of beds in hospital H.

(1.c) Identification of the most convenient level of retrofitting intervention.

The choice of the retrofitting level (levels 1–4) should be made on the basis of a cost–benefit analysis. Benefits associated with retrofitting up to level 4 have been computed for six hospitals, the most important three from analyses (1.a) and (1.b). This allows identification of the most convenient level of retrofitting intervention. The intervention costs at the various levels are not dealt with in this paper.

(1.d) Assessment of effectiveness of common emergency strategies.

Two common emergency measures after a major earthquake consist of increasing the nominal capacity of hospitals, i.e. letting more patients in each hospital by adding beds, and installing a camp hospital in the epicentral area so as to be as near as possible to the casualties concentration. The effectiveness of such strategies has been assessed by comparing the mean value of the distance per casualty in the hospital network as is with those computed after increasing the nominal capacity of hospitals by a factor of 2 up to 20, and after installing a camp hospital at the epicentral location with number of beds ranging between 5 and 500.

(1.e) Identification of highest hazard sub-regions.

A scenario analysis has been carried out to identify the highest hazard sub-regions in Abruzzo. Seismogenic area 33, which has been found to be the most important on the overall reliability, has been divided into 15 sub-regions (see Figure 8) and mean values of distance per casualty, conditioned to earthquakes in one of the subregions, are compared.

This allows identification of the areas that would first need the building of new hospitals; in fact, a high value of the distance per casualty, conditioned to epicentres belonging to one sub-region, indicates, assuming a constant population density, which is the nearly the case in the territory around seismogenic area 33 (see Figure 2), that people living in that sub-region will take, on average, a longer time to reach a hospital, and that the optimal location for a new and low-fragility hospital is that sub-region.

The results of this analysis have also been used to determine the distance of hospitals with respect to the epicentre, which is likely to be filled up. This should be used in civil protection strategies in order to design emergency plans: hospital managers should be instructed to send excessive casualties away from this area.

For each of the subregions, the mean value of the coefficient of occupation of hospitals, versus their distance from the epicentre, has been computed and plotted on a graph; it should be remembered that the coefficient of occupation, in normal conditions, is assumed equal to 70%.

The analysis has been performed by a sub-region in order to separately identify their behaviour; however, all sub-regions appeared to give approximately the same results.

Analyses (2) consist of three types of investigations (2.a–2.c):

(2.a) Computation of decrease of damage to the hospitals, in terms of mean value of beds damaged, after retrofitting of hospitals.

This was computed according to:

$$i2\mathrm{a}(H, F) = \{b_H(0) - b_H(F)\} \cdot \{\lambda(33) + \lambda(34) + \lambda(35)\} \tag{6}$$

where $b_H(0)$ is the mean value of damaged beds in hospital H, with no retrofitting intervention (fragility curve at level 0), given a seismic event, $b_H(\mathrm{F})$ the mean value of damaged beds in hospital H, with retrofitting intervention (fragility curve at level F), given a seismic event, $\lambda(n)$ the activity (number of earthquakes per year) of seismogenic area n.

The value in equation (6) is the expected number of beds gained in one year due to retrofitting of hospital H at level F. Of course, this depends only on the fragility and hazard of each hospital and not on the system-like behaviour of hospitals.

(2.b) Computation of the decrease of damage to the hospitals, in terms of mean value of beds damaged, after retrofitting of hospitals one at a time, for unit retrofitting cost

For the reasons explained in (1.b), it was decided to also consider the value of

$$i2\mathrm{b}(H, F) = \{b_H(0) - b_H(F)\} \cdot \{\lambda(33) + \lambda(34) + \lambda(35)\} \cdot \frac{1}{\mathrm{nb}(H)} \tag{7}$$

which yields the expected number of beds gained in one year due to retrofitting of hospital H at level F, per retrofitted bed unit.

(2.c) Computation of the pay-back period for retrofitting interventions.

Reciprocal of the value in equation (7) yields the first-order approximation[10] to the average number of years before the retrofitting pays for itself, i.e. the pay-back period.

Analysis 1.a, b: identification of hospitals with maximum associated benefit

The average distance per casualty in normal conditions is 5 Km (see Figure 1); this value increases to $r(0) = 20{\cdot}1$ Km (after an earthquake); the maximum obtainable improvement, if retrofitting was made at such a level that hospitals were not fragile, is at the value of $r(\infty) = 11{\cdot}7$ Km.

Improvement, for each hospital and retrofitting level, has been computed according to equation (4) and shown in Figures 9–12 for results normalized to available beds (expression (5), analysis 1.b).

Results of (1.a) show that the ranking of hospitals does not significantly change whether upgrading to level 1 or 2. The three most important hospitals for these cases are numbers 10, 2 and 3.

A considerable improvement is given by the first three hospitals ($i1.\mathrm{a}(H,1) \geqslant 9{\cdot}5\%$); from the eighth hospital on, $i1.\mathrm{a} \approx 3\%$ and remains small for level 2 also.

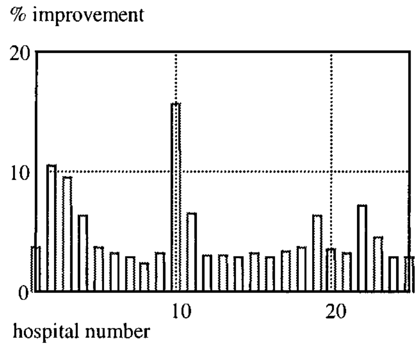

Figure 9. Improvement with level 1 fragility

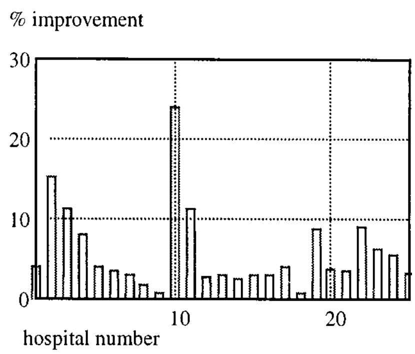

Figure 10. Improvement with level 2 fragility

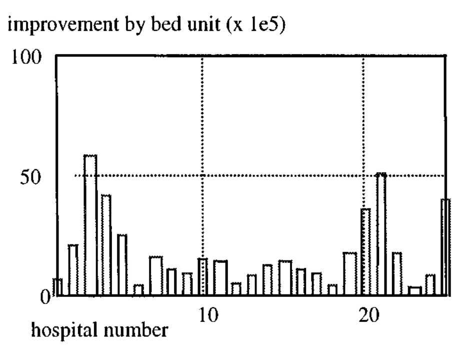

Figure 11. Improvement by bed unit with level 1 fragility

Hospital 10 is, unsurprisingly, the second bigger hospital in the region (see Table I) while hospital 2 is of medium size. The high ranking of hospital 3, in Pescina, a very small one but in a site with high risk and considerable population density, already signals that it will again be among the most important if one considers improvement by bed unit.

In fact it ranks as the first one in analyses (1.b), while the remaining part of the ranking completely changes with respect to (1.a). Negligible differences between results relative to upgrading at level 1 or 2 appear. The three most important hospitals are numbers 3, 21 and 4.

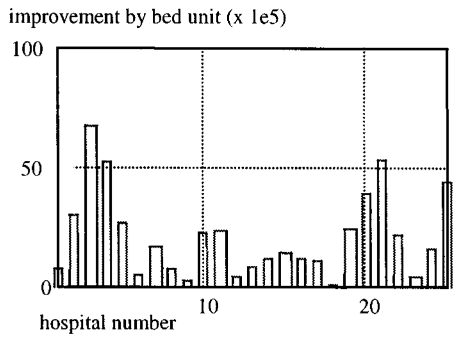

Figure 12. Improvement by bed unit with level 2 fragility

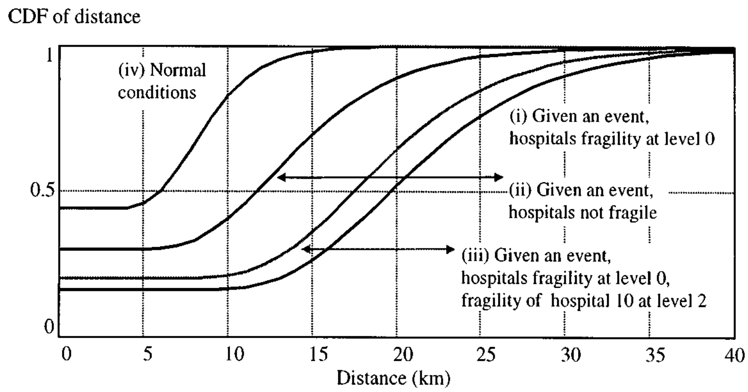

Figure 13. Comparison of CDFs of distances

Analyses (1.b) give a better insight in the benefits obtained per unit investment. The most effective retrofitting interventions are those performed on hospitals in high hazard and population sites. The first five hospitals show a value for $i1b(H, 1)$ larger than $35e-5$; large values of improvements (say larger than $10e-5$) are, however, shown by the first 16 out of 25 hospitals. Further, due to the relatively low seismicity of this region, from the 15th hospital on, there is essentially no increase in benefit retrofitting to level 2 as compared to level 1.

CDFs of distances for cases 0 (curve i), ∞ (curve ii), for normal conditions in Abruzzo (no earthquake), (curve iv), and for retrofitting level 2 of hospital 10, the most important one for analysis (1.a), are plotted in Figure 13.

The difference between CDF (iv) and (ii) is due to the filling of hospitals in the epicentral area, which compels casualties to move away from that zone, while the difference between curves (ii) and (i) is due to the fragility of hospitals, which reduces the number of available beds; curve (iii) shows improvement with respect to the situation (i), even with just one retrofitted hospital.

Analysis 1.c: identification of the most convenient level of retrofitting intervention

It is intuitive that the overall reliability improvement is a monotonically increasing function of the retrofitting level. The rate of increase, in terms of distance per casualty, is a decreasing function of the retrofitting level. This can be already observed from the results in Figures 9–12: the improvement for

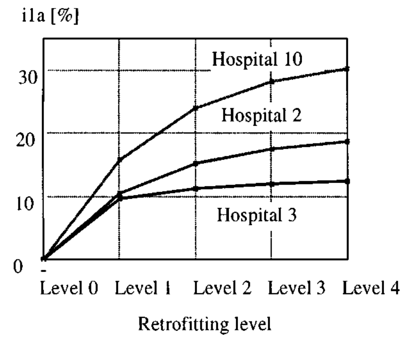

Figure 14. i1.a as a function of the retrofitting level

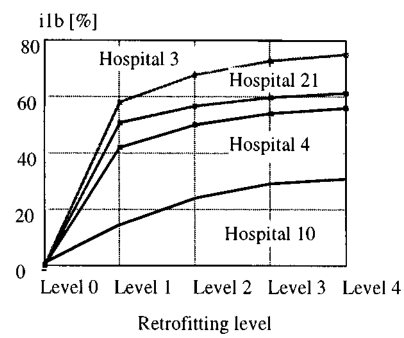

Figure 15. i1.b as a function of the retrofitting level

retrofitting hospital 10 at level 1 is worth 15·7% of the maximum improvement; retrofitting at level 2, gains a relative improvement worth $23{\cdot}9\% - 15{\cdot}7\% = 8{\cdot}2\%$, which is about half of that at the previous level.

A comprehensive analysis has been conducted with the three most important hospitals according to the results of analyses (1.a), i.e. numbers 10, 2 and 3, and (1.b), i.e. numbers 3, 21 and 4. The fragility of each hospital has been moved parallel to itself by half a MM degree, as shown in figure 6

The results in terms of improvement quantified via equation (4) for hospitals 10, 2 and 3 and via equation (5) for hospitals 3, 21 and 4 is plotted in Figures 14 and 15. The improvement by bed unit i1.b is shown for hospital 10 for comparison (Figure 15), the most important from analysis 1.a.

As a general remark, one can see that the trend is towards a constant value for high retrofitting levels and that this is reached at a lower level for less effective retrofitted hospitals.

For instance, with reference to Figure 14, benefits coming from hospital 10 are significant up to level 4, whereas retrofitting hospital 3 beyond level 1 brings about much less improvement.

This would be good news, if confirmed for different seismogenic areas, because, it would indicate that the best strategy is to significantly strengthen a few hospitals and make minor retrofitting interventions on most hospitals. However, it must be stressed that the results are highly problem dependent; it seems reasonable to state that for higher regional seismicity or population distribution or hospitals' fragility, many more, or maybe all, hospitals would have an important function in minimizing time for casualties to be cured.

Analysis 1.d: *assessment of effectiveness of common emergency strategies*

The effects of two common emergency measures after a major earthquake on system response are increasing the nominal capacity of hospitals and installing a camp hospital in the epicenter as presented in Figures 16 and 17.

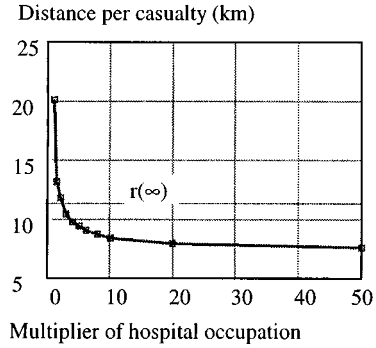

Figure 16. Improvement with increase in hospitals' occupation

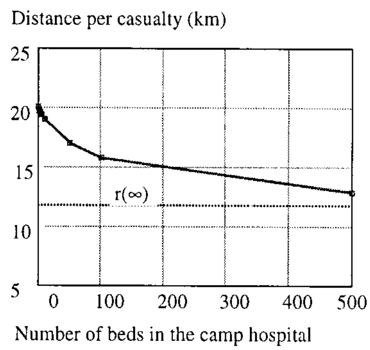

Figure 17. Improvement with camp hospitals' installations

The decrease in distance per casualty with an increasing number of beds in each hospital is shown in Figure 17; the ratio of actual capacity to nominal capacity is termed the multiplier of hospital occupation.

The decreasing trend is clearly visible; multipliers greater than 5 are unrealistic but the analysis has been extended up to the value of 50 to get the asymptotic value of the behaviour.

One can see that an increase to about 5 leads to the value of $r(\infty)$, i.e. the value obtained for all the hospitals undamageable.

Installation of camp hospitals as a post-disaster intervention measure is currently implemented in some countries to an extended degree. In France,[11] for instance, the current strategy consists of locating packed small (25 beds) and big (500 beds) portable camp hospitals throughout the country (35 small and 20 big camp hospitals are currently exploitable). These can be moved and assembled where necessary in a short time.

Hence, it was decided to explore the effect of exploiting a camp hospital of up to 500 beds assembled in the epicentral area soon after the earthquake. Results are shown in Figure 17.

A clear decreasing trend is observed, with interesting improvement in the overall behaviour.

It has to be stressed that installation of camp hospitals is particularly interesting since, though the problem of reaching the installation may be critical, it can be set-up immediately.

Analysis 1.e: *identification of highest hazard sub-regions*

The mean values of distance per casualty in each sub-region of seismogenic area 33 are shown in Figures 18 and 19; values are ordered decreasingly in Table III.

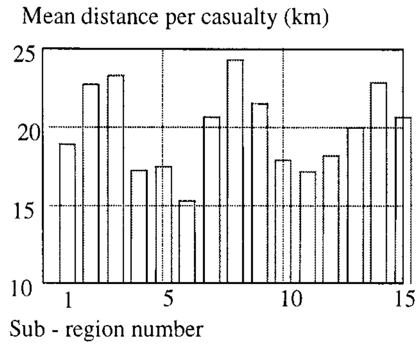

Figure 18. Mean distances per casualty in sub-regions 1–15

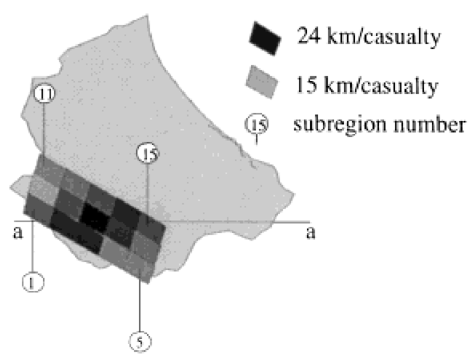

Figure 19. Mean distances per casualty in sub-regions 1–15

Table III. Results of analyses 1.e

Sub region	8	3	14	2	9	7	15	13	1	12	10	5	4	11	6
Distance per casualty	24·3	23·3	22·9	22·7	21·4	20·6	20·6	19·9	18·9	18·2	17·8	17·4	17·2	17·2	15·3

It has to be first observed that means in the subregions are rather spread about the general mean (maximum and minimum are, respectively worth the general mean $= 20 \pm 5$ km, i.e. the mean $\pm 25\%$). Worst situations are lined along the east–west direction (line a–a in Figure 19) with the worst value at the central subregion. Results are explanable if one considers that, population density being similar, inhabitants of the western sub-regions are nearer to hospitals as compared to inhabitants of central and eastern sub-regions. Inhabitants in eastern sub-regions have, in fact, the possibility of using hospitals in Lazio and Molise.

This very analysis was used to determine the trend in the mean value of the hospitals' coefficient of occupation (c.o.) as a function of the distance from the epicentre. Since this analysis was meant to be representative of the situation for strong-motion earthquakes, simulation was performed with a minimum intensity of 9 MM. Results, not plotted here for the sake of brevity, show that within 50 km from the

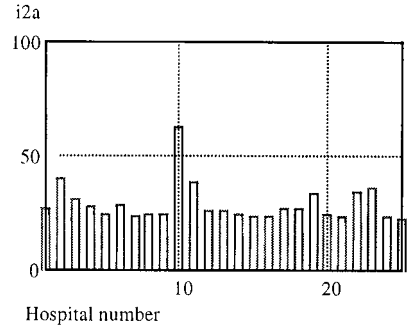

Figure 20. Improvement with level 1 fragility

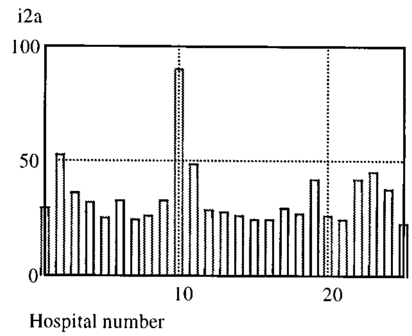

Figure 21. Improvement with level 2 fragility

epicentre the c.o. is equal to or larger than 98%, and that it linearly decreases to about 90% at 80 km from the epicentre, almost irrespective of the sub-region considered.

Analyses 2.a–c: decrease in hospitals damage and pay-back period for the retrofitting interventions

The mean value of the number of bed–losses per year for the regional system as is, is worth 998·1; this value has been compared with the ones obtained assuming that each hospital, is individually retrofitted at level 1 or 2. The difference between the two cases, computed according to equation (6), yields the annual average decrease in bed losses.

Results are plotted in Figures 20 and 21, for retrofitting levels 1 and 2, respectively.

The annual gain in each hospital, divided by the number of beds, formula (7), yields the average value of the gain per retrofitted bed. Results are shown in Figures 22 and 23.

The reciprocal of the average value of the annual gain per bed unit is the first-order approximation[10] to the pay-back period, i.e. the time to wait for the retrofitting intervention to pay for itself. This is shown in Figures 24 and 25, for each hospital and for levels 1 and 2.

Analysis (2.a) shows that the ranking of hospitals does not significantly change for retrofitting levels 1 or 2. The three most important hospitals are numbers 10, 2 and 11. The ranking changes when comparing improvements by unit retrofitting cost (analysis 2.b), since the three most important hospitals are numbers 21, 25 and 20. Note that the ranking according to these analyses is still different with respect to those obtained in the previous analyses.

Analysis (2.c) shows that the overall hospital situation is rather critical, since the pay-back periods, in years, are very small. It has to be stressed that these results must be understood as the average outcome over

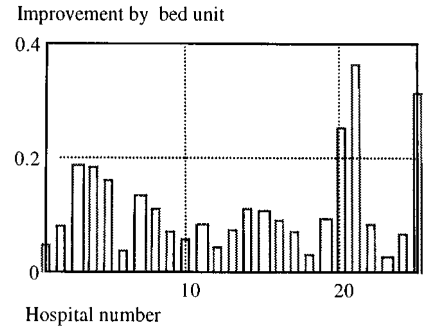

Figure 22. Improvement by bed unit with level 1 fragility

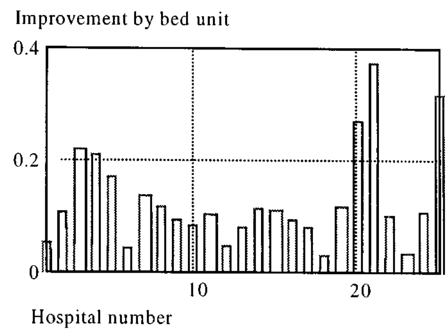

Figure 23. Improvement by bed unit with level 2 fragility

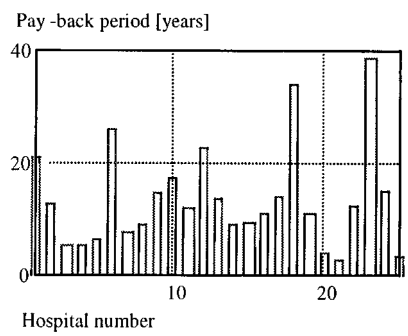

Figure 24. Pay-back period with level 1 retrofitting

a large number of years; average refers to the fact that they have been first computed conditioned to an event and, after multiplication by the sum of mean rates in each seismogenic area, the result conditioned to one year.

INTERVENTION STRATEGY BASED ON THE OBTAINED RESULTS

A possible strategy for the seismic upgrading of the regional system can be retrofitting of all hospitals at level 1, and retrofitting at level 4 of a limited number only. Such a strategy looks reasonable in view of the fact

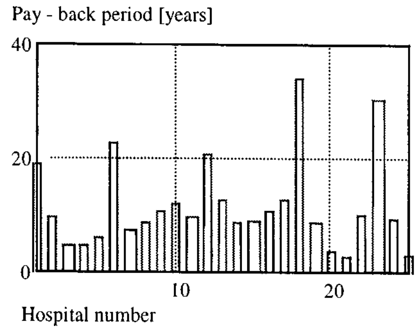

Figure 25. Pay-back period with level 2 retrofitting

Table IV. Improvements for different retrofitting strategies

Intervention	Distance per casualty (Km)	$i1a(\%)$
Generalized level 1	15·71	52·3
a	14·9	61·9
b	13·9	73·8
c	11·8	98·8

that level 1 can be achieved within the usual maintenance operations carried out in the hospitals with negligible budget increase, whereas level 4 requires a relevant financial effort and the partial or total closure of the structure.

Since the distance per casualty, which accounts for the behaviour of the hospitals as a network system, is a more informative performance index as compared to bed losses, which only quantifies the seismic risk at each hospital location, the choice of the hospital to retrofit at level 4 is made on the basis of their ranking in analyses 1.b, in order to maximize the benefit for the users (index type 1), for unit cost intervention (index type b).

Three strategies have been considered here:

a. retrofitting of hospitals with $i1b(H, 2) \geqslant 50\%$, i.e. hospitals 3, 21 and 4 (which collectively count 379 beds)
b. *a* plus retrofitting of hospitals with $i1b(H,2) \geqslant 30\%$, i.e. add hospitals 25, 20 and 2 (total of 1047 beds)
c. *a* plus *b* plus retrofitting of hospitals with $i1b(H,2) \geqslant 20\%$, i.e. add hospitals 5, 19, 11, 10 and 22 (total of 3525 beds)

Table IV shows the results in terms of mean distance per casualty and associated index $i1a$.

A substantial improvement is obtained already for the near-no-cost intervention of generalized upgrading to level 1 and further decrease in the distance per casualty is observed for the other interventions in the list.

If the intervention strategy followed results of analysis 1.a, for comparison, upgrading to level 4 of hospital 10, the first one in ranking, with 1073 beds ($\approx$ 1047 beds, corresponding to intervention *b*), would yield a mean value of the distance per casualty equal to 14·3 Km (i1.a = 68%); the gain obtained by using the results of analysis 1.b would be even more evident whether conditioned to more intense seismic events than those considered here.

Further, if generalized level 1 upgrading was not enforced (current fragility level of hospitals = 0), one should upgrade at level 4 a minimum of 3500 beds, i.e. all the hospitals in intervention type *c*., to obtain the same result associated with intervention *b*. (again 1047 beds): the saving of financial resources shows very clearly.

CONCLUSIONS

A procedure for the evaluation of seismic safety for a hospital regional system (HRS) is presented. The main parameter employed to measure the efficiency of the system is the mean distance (MD) that injured people have to cover to reach an unfilled hospital. In fact after a seismic event, many hospitals can be completely or partially out of order, while the request of medical care has a peak; one can therefore expect that the hospitals around the epicentre easily fill their reduced capacity. The MD index used here is, in the authors' opinion, much more meaningful than those accounting only for direct damages to the system and should be weighted more than those of the latter class in decision taking.

The method developed is applied to a case study region, Abruzzo in Italy. Various results of interest have been obtained:

- which is the present level of safety,
- which hospital or group of hospitals should be first retrofitted i.e. the ones whose improvements mostly reduces MD,
- which retrofitting level is more convenient,
- which are the effects of some emergency measures like installing camp hospitals or increasing hospital capacity for an emergency.

Results show a current high vulnerability for the system, whose efficiency is obviously of dramatic importance in post-earthquake conditions. A clear ranking is obtained among the hospitals, showing those more critical for the HRS.

Possible strategies for retrofitting are then evaluated:

- retrofit a group of hospitals to a high level of *strength*, on the basis of the ranking previously found;
- retrofit all hospitals at a minimum level, based on simple interventions which are essentially based on non-structural elements and equipment bracing, and of some hospital to a high level of *strength*.

Results show that the second choice is very effective.

In the paper a certain number of simplified assumptions have been considered; these can be removed and more accurate models introduced without changing the procedure. The first model improvement could be a more accurate definition of the fragility of the hospitals, which should be based on specific evaluations; the second could be the model of casualty versus local intensity. For the latter a sensitivity analysis was carried out varying the curve in Figure 4; results showed low sensitivity to this parameter in the sense that the ranking of hospitals remains unchanged in addition to the relative improvements in MDs.

Finally, the description of road communication and of their fragility could be of relevant interest, especially in regions such as the ones considered here, where mountains give important limitation to an homogeneous distribution of communication lines on the territory. One should, however, consider that the model would become much more cumbersome with respect to the one presented here which is in fact extremely prone to sensitivity analyses, and is well representative of developed regions. In the case of regions with less roads, which is usually the case of underdeveloped countries, the consideration of a road network is simple and straightforward.

The method proposed seems to be an interesting tool to support decision strategies in the retrofitting of an HRS to a desired safety level. This is a very crucial point and it is in fact well known that seismic retrofitting of existing hospitals is a world-wide unsolved problem.

APPENDIX: EXAMPLE OF THE ADOPTED PROCEDURE

The simple system of Figure 26 is studied, consisting of two municipalities ($M1$ and $M2$) and seven hospitals ($H1$–$H7$). The steps of the procedure read as follows:

1. An earthquake strikes at the epicentre with known intensity.

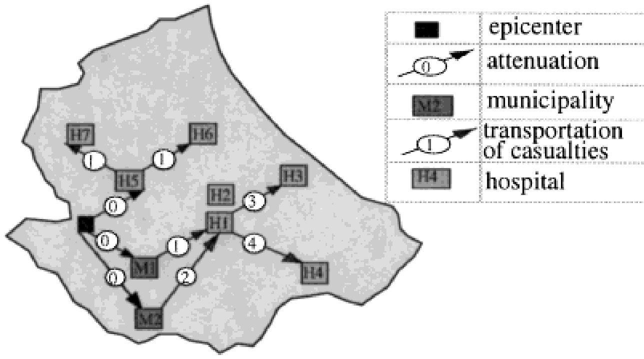

Figure 26. Example of the adopted procedure

2. Intensities at hospitals and municipalities locations are hence computed.
   This is indicated with the arrows containing the 0 value, meaning time is elapsed from that moment.
3.
   3.1
      3.1.1 At municipalities $M1$ and $M2$ casualties are sampled
      3.1.2 at hospitals the structural damage is sampled
      $H2$ results in having no extra capacity, but succeeds in treating its patients; $H5$ has to move some of its casualties to other hospitals (step 3.1.2); the remaining hospitals are undamaged
   3.2
      3.2.1 Casualties are moved from $M1$ and $M2$ to the nearest hospital, $H1$, without any information on its capability of admitting patients; casualties $M1 \rightarrow H1$ arrive at time 1 whereas casualties $M2 \rightarrow H1$ arrive at time 2
      3.2.2 Casualties exceeding the capacity of $H5$ have to be moved assuming information on surrounding hospital capacity is available: some of them are transported to $H6$, which is then filled up, and the remaining part to $H7$
      At time 1, *hence*, $H5$ *and* $H6$ *are filled up while* $H7$ *and* $H1$ *through* $H4$ *have unused capacity.*
4. At time 2 casualties $M2 \rightarrow H1$ reach $H1$; $H1$ gets filled up and has to move some of the new arrivals to other hospitals assuming information is available
5. $H2$ has no capacity and hence extra casualties are partly moved to $H3$, up to $H3$ capacity; the remaining part is moved to $H4$. Casualties $H1 \rightarrow H3$ reach $H3$ at time 3 while casualties $H1 \rightarrow H4$ reach their destination at time 4.
6. At the end of the simulation, the total number of bed losses and the average distance per casualty are output. These constitute the results of one experiment. If the c.o.v. of estimators of the mean value of performance indexes is lower than the prescribed value, the procedure stops; otherwise it continues restarting from step 1.

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REFERENCES

1. C. Nuti, G. Monti, D. Pierucci and S. Santini, 'Affidabilità sismica degli Ospedali', *Atti del 7° Convegno Nazionale di Ingegneria Sismica*, Siena, Italy, 1995.

2. G. Monti and C. Nuti, S. Santini, 'Seismic assessment of hospital systems', *Proc. 11th WCEE*, Acapulco, Mexico, 1996.
3. G. Monti and C. Nuti, 'A procedure for assessing the functional reliability of hospital systems', *Structural Safety*, 18, (4) (1996).
4. DGXII European Commission, 'Hope: Seismic risk assessment and mitigation of hospital facility networks', *Contract EV5V CT93 0297*, Final Report STIN, 1997.
5. T. Sanò, G. Di Pasquale and G. Orsini, 'Seismic risk assessment and mitigation of hospital facility networks, task1: typical damage evaluation based on past earthquakes: Irpinia (1980), and Friuli (1976) earthquakes', *Rapporto ANPA-DISP within contract CEE EV5V CT93 0297*, (1994).
6. R. Colozza and R. De Marco, 'Metodologie di utilizzo dei dati dell'atlante della classificazione sismica. Il Test Abruzzo', *Servizio Sismico Nazionale*, 3, 1988.
7. ISTAT, Censimento della popolazione italiana, 1991.
8. A. Coburn and R. Spence, *Earthquake Protection*, Wiley, New York, 1992.
9. R. Giannini, A. Giuffrè, C. Nuti, F. Ortolani and P. E. Pinto: 'Valutazione quantitativa del rischio sismico. Metodologie ed applicazione alla città di Subiaco', *Ingegneria Sismica*, Anno I, 1 (1984).
10. A.H.-S. Ang and W. H. Tang, *Probability concepts in engineering planning and design*, Vol. 1, J. Wiley, New York, 1975.
11. Cétè Méditerranée, 'Plan d'organisation des sécours en cas de catastrophe sismique', *Dossier 96366/73*, 1996.